Limits on Four-Top Production from the ATLAS Same-sign Top-quark Search

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We repurpose the recent ATLAS search for same-sign top quarks in data with 1.0 fb^{-1} in the context of a search for production of four top quarks. Using the null results of that search, we place limits on the four-top-quark production cross section of about 1 pb. These limits are larger than the expected Standard Model rate for four-top-quark production, but are already strong enough to place interesting constraints on models which enhance that rate. We interpret these results in the context of models in which the right-handed top quark is composite and find limits on the compositeness scale of about 700 GeV.

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The top quark, as the heaviest fermion of the Standard Model (SM), and the only one to have a mass of "natural" size at the electroweak scale, is a natural laboratory to explore physics beyond the Standard Model. In particular, while production and decay of top quarks seems to be roughly in line with SM expectations [1] (however, see [2]), many open questions remain. For example, many models such as top-color [3] and top-flavor [4] posit a new interaction unique to the top quark, which ultimately drives electroweak symmetry-breaking. Such an interaction would most naturally reveal itself through multi-top-quark production [5, 6], a process requiring at least $4m_t \sim$ TeV partonic energies that are just now becoming accessible to the Large Hadron Collider. Even if the interactions of the top quark itself are more prosaic, there may still be enhancements of the four-top-quark production rate arising from gluino decays [7] (which also lead to additional sources of missing energy in the events) or exotic colored scalar [8] decays.

One particularly fascinating vision for physics which contributes to multi-top-quark production are models where the top quark is composite [5, 6, 9–11]. Such models fit easily within the paradigm of strongly coupled theories of electroweak symmetry-breaking [12] dual to Randall-Sundrum (RS) models of an extra dimension [13], but also are interesting in their own right, as complements to searches for compositeness of the light quarks and/or leptons. Without a detailed picture for the UV physics, it is difficult to make firm predictions for how a composite top quark would manifest at the LHC. However, generic features such as a four-top-quark contact interaction or the presence of a color-octet vector particle with strong coupling to the top quark (reminiscent of the RS Kaluza-Klein gluon [14]) are expected to appear in wide classes of models [6]. Limits from the Tevatron derived from the rate of $t\bar{t}$ pair production are rather weak [6, 10], placing essentially no useful bound on the compositeness scale if there are modest cancellations in the leading modifications to the gluon-top-anti-top vertex.

Given the rich physics potential of multi-top-quark events, in this letter we perform an analysis of LHC data to search for four-top-quark production. We rely on the cases in which either both top quarks or both anti-top-quarks decay leptonically, leading to a same-sign dilepton signature with small expected SM background. Our results are derived from the recent ATLAS same-sign dilepton (plus jets and missing transverse momentum) search [15] based on 1.0 fb^{-1} of integrated luminosity, which was originally designed to search for same-sign top-quark pair production and fourth generation quarks. For an alternate proposal to search for events with four top quarks in early LHC running, see Ref. [16]. We interpret our results in the context of four-top-quark production through a color-octet (ρ_o) or color-singlet (ρ_s) vector resonance, and for SM-like kinematics of four-top-quark production.

Events are selected with [15]:

- Two same-sign leptons (with no veto on additional leptons):
- Events containing like-flavor leptons are vetoed if $|m_{\ell\ell} - m_Z| \leq 10$ GeV;
- Missing transverse momentum of at least 40 GeV;
- Event H_T (scalar sum of lepton and jet transverse momenta) at least 350 GeV.

The number of selected events and the estimates of the SM background contributions are shown in Table I [15].

In order to interpret these as limits on another process, we first convert the ATLAS limits on the cross section of a specific model into a generic limit on the number of events, N, due to a new source. Using

$$N = \epsilon \times \sigma \times \mathcal{L}$$

where ϵ is the fraction of produced events satisfying the event selection, σ is the production cross section and $\mathcal{L}$ is the integrated luminosity of the data sample. For $b' \to tW$ with $m_{b'} = 350$ GeV, the ATLAS selection gives

	$e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$
Fake	$1.0^{+0.6}_{-0.7}$	$1.7^{+0.7}_{-0.6}$	$3.8^{+1.9}_{-1.8}$
Charge flip	$0.6^{+0.3}_{-0.1}$	$0^{+0.1}_{-0.0}$	$0.7^{+0.3}_{-0.1}$
Real	$2.7^{+0.7}_{-1.5}$	$2.6^{+0.7}_{-0.9}$	$6.7^{+1.3}_{-3.1}$
Total	$4.4^{+0.5}_{-0.7}$	$4.3^{+0.9}_{-1.1}$	$11.2^{+2.5}_{-3.6}$
Data	3	3	12

TABLE I: Predicted number of SM background events and observed data with two same-sign leptons, at least two jets, MET > 40 GeV and $H_T > 350$ GeV, adapted from Ref. [15]. Uncertainties are statistical and systematic in quadrature.

$\epsilon = 0.02$ and results in an upper limit of $\sigma < 800$ fb at 95% confidence level [15]. Therefore $N < 16.6$ at 95% confidence level. Applying this limit to derive a cross-section limit for an arbitrary process requires knowing the selection efficiency (ϵ) for the model of interest.

We simulate four-top-quark production using MADGRAPH [17], with PYTHIA [18] for showering and hadronization and detector simulation with a parametric fast simulation tuned to match ATLAS performance [20], for four-top-quark production with SM-like kinematics, and for models with color-octet or color-singlet vector resonances (see Fig. 1). The SM prediction for four-top-quark production is around 5 fb [6], well below the current experimental sensitivity, implying that any new physics contribution to which the LHC is currently sensitive will have negligible interference with SM four-top-quark production processes. Efficiencies for SM-like four-top-quark as well as color-singlet ρ_s or color-octet ρ_o are shown in Fig 2. Some representative kinematic distributions are shown in Fig. 3. To validate our efficiency calculation, we compare published ATLAS efficiencies for $b' \to tW$ to efficiencies we measure using the identical production, showering, hadronization and detector simulation as described above; we find good agreement between our efficiencies and the published ATLAS efficiencies. The efficiency for models with the new ρ particle rises with m_ρ for low-mass due to increases in the lepton and jet momenta; at high mass, it falls due to low lepton isolation efficiencies from the increased activity and the greater top-quark and W boson boosts.

Limits are computed from $\sigma < N/(\epsilon \times \mathcal{L})$, and are shown in Fig 4. The limits require a cross section for anomalous sources of four-top-quark production to be less than about 1 pb, and are similar for both models containing a ρ_o or ρ_s, as well as models which produce the four top-quarks with SM-like kinematics. A re-analysis of CMS dilepton and trilepton data was performed [19] in a similar spirit and leads to comparable bounds. For moderately strongly coupled ρ_o ($g_{\rho t\bar{t}} \sim 1$), the bound on the ρ_o mass is around 700 GeV, significantly improving

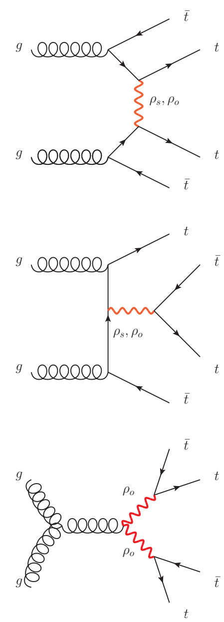

FIG. 1: Representative diagrams of four-top-quark production including the new particles ρ_o (color octet) and ρ_s (color singlet). In each case, there is a representative SM diagram with a gluon in place of a ρ.

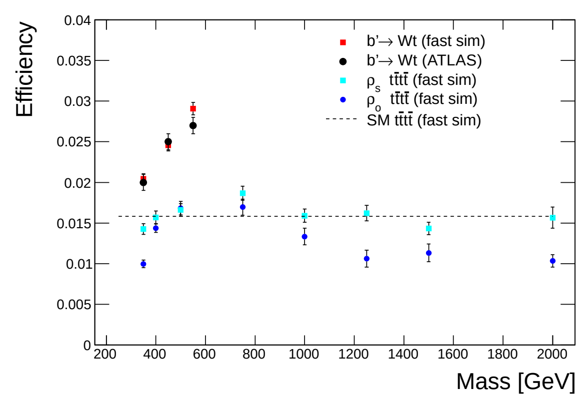

FIG. 2: Efficiency of the selection for resonant and SM four-top-quark production. For validation, we compare the efficiency using the fast simulation to the published ATLAS efficiencies [15].

upon the existing Tevatron limits. Bounds on a four-top-quark contact interaction are currently weak enough so as to invalidate any hope that the effective theory is a good description, but should become interesting with more data at higher center-of-mass energy [9, 10].

In closing, we have set bounds on the rate of four-

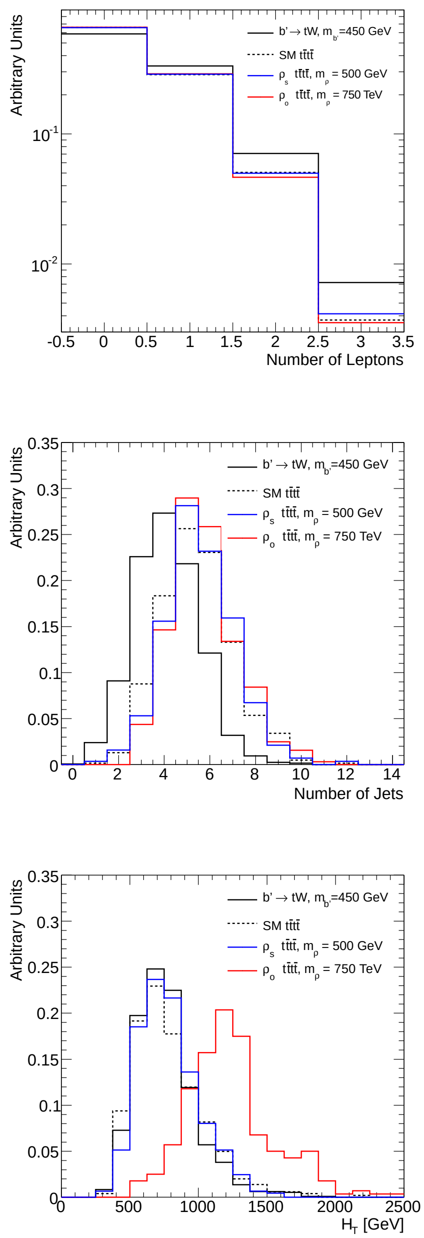

FIG. 3: Distribution of kinematic quantities for various models. Top, lepton multiplicity before any selection. Center, jet multiplicity for events with same-sign dileptons. Bottom, H_T after all selection requirements other than $H_T > 350$.

top-quark production, using the recent ATLAS same-sign dilepton search. While this search is effective in placing interesting limits on four-top-quark production, it was optimized for events containing two top quarks, and so one can imagine improving upon it by using the larger set of handles available from the decay products of four top quarks. Our work is only a first step into what should be a fruitful age of multi-top-quark searches at the LHC.

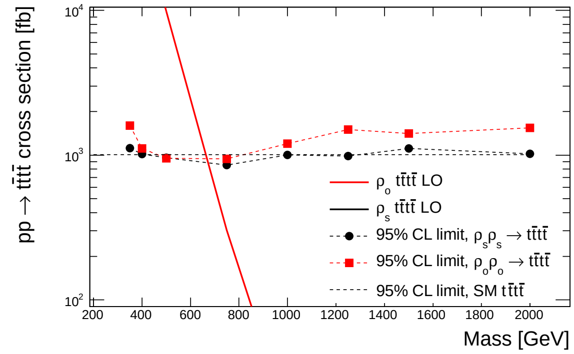

FIG. 4: Upper limits at 95% confidence level on production of a four-top-quark final state via SM or ρ_s, ρ_o production. Also shown is leading-order predictions in the color-octet model; the prediction for SM four-top-quark or color-singlet models are less than 10 fb.

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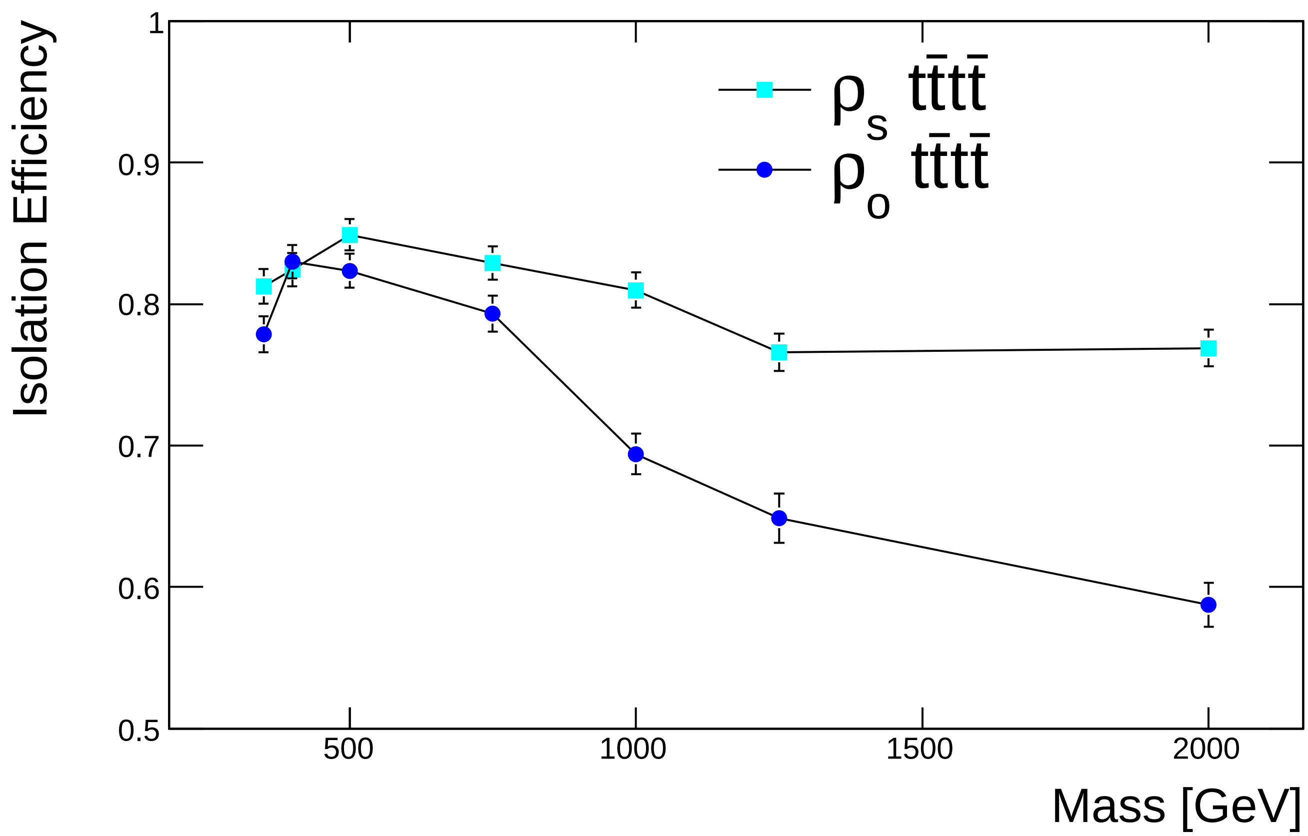
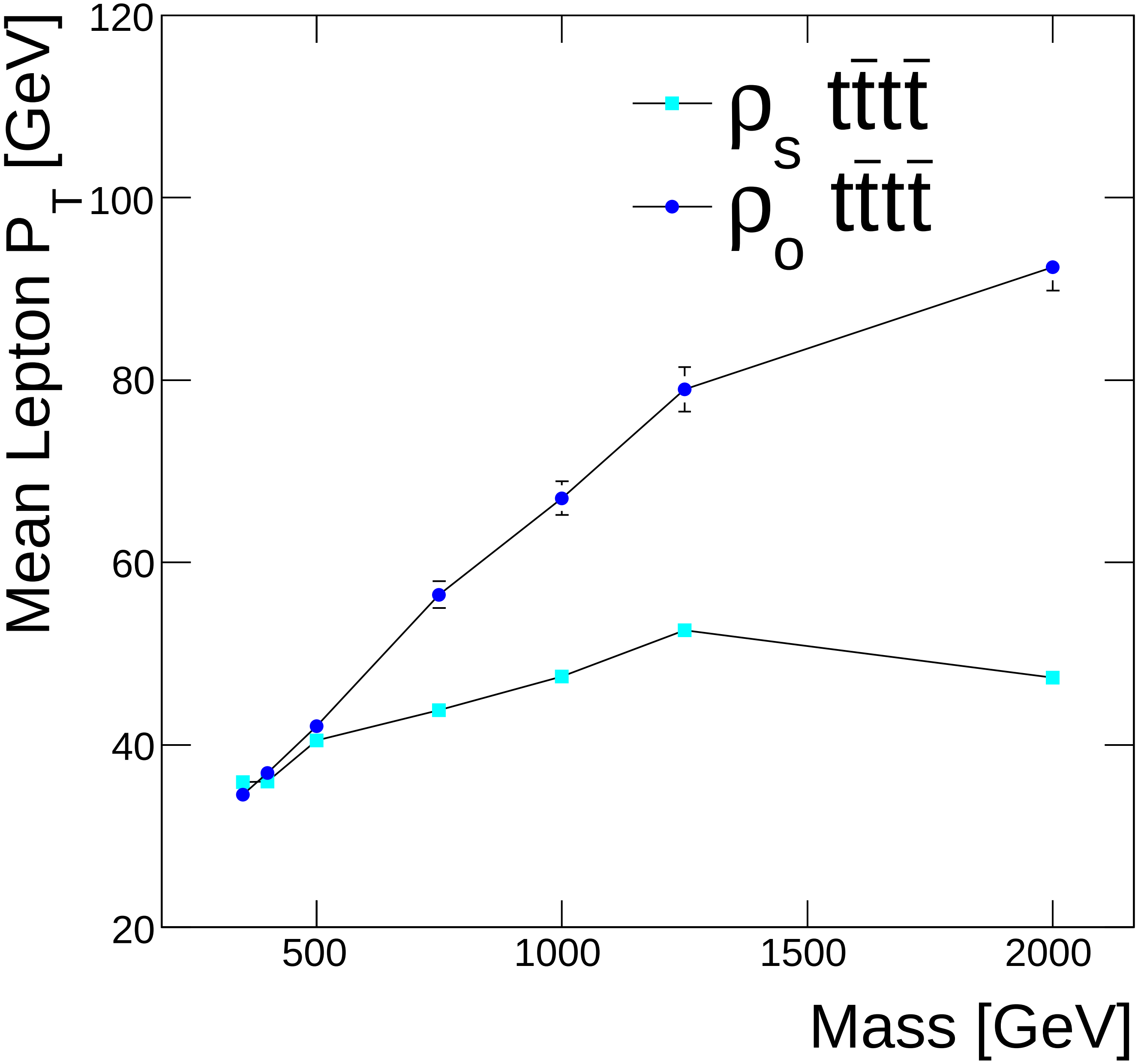


Isolation Efficiency
1
0.9
0.8
0.7
0.6
0.5
500
1000
1500
2000
Mass [GeV]
ρ_s $t\bar{t}t\bar{t}$
ρ_o $t\bar{t}t\bar{t}$



Mean Lepton P_T [GeV]
120
100
80
60
40
20
500
1000
1500
2000
Mass [GeV]
ρ_s $t\bar{t}t\bar{t}$
ρ_o $t\bar{t}t\bar{t}$